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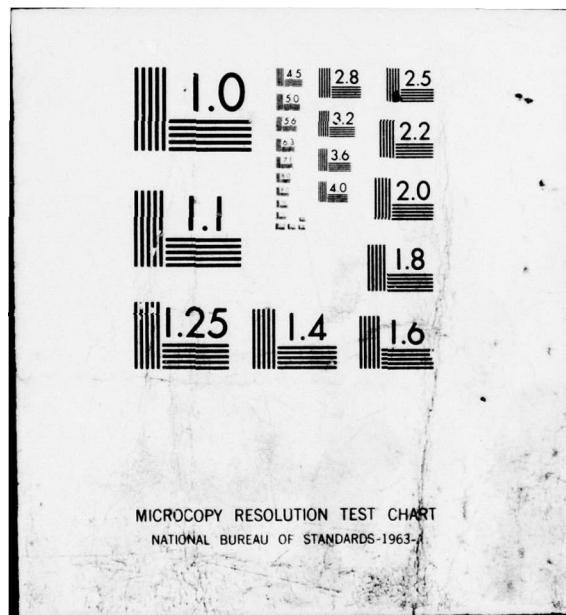
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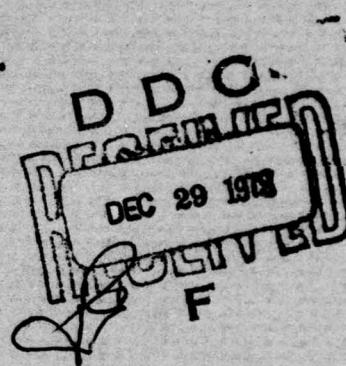
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SECOND QUARTER PROGRESS REPORT ON  
PLASMA THEORY AND SIMULATION

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SECOND QUARTER PROGRESS REPORT  
on  
PLASMA THEORY and SIMULATION.

9 Rept. for 1 Apr. 1 — 30 June 30, 1978

Work accomplished during the Second Quarter of 1978 is reported here.

Our research group uses both theory and simulation as tools in order to increase the understanding of instabilities, heating, diffusion, transport and other phenomena in plasma. We also work on the improvement of simulation, both theoretically and practically.

Our staff is — 10

Professor C. K. Birdsall  
(Principal Investigator) 191 M Cory Hall (642-4015)

Drs. Yoshi Matsuda,  
William Fawley  
(Post Doctorates) 119 ME Cory Hall (642-3477)

Yu Jiuan Chen, Douglas Harned,  
Jae Koo Lee, Ali Peiravi  
(Research Assistants) 119 MD Cory Hall (642-1297)

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## Section I PLASMA THEORY

### A. DRIFT CYCLOTRON INSTABILITY

J. K. Lee

We use the dispersion equation solver, ROOTS<sup>1</sup>, to obtain the results of the linear theory (growth rates, etc.) as a guideline of and a comparison with future simulations of density-gradient-induced instabilities, namely, drift cyclotron (DC), drift cyclotron loss cone (DCLC), or lower hybrid drift (LHD) instabilities.

For the drift cyclotron instability, ROOTS with the local approximation provides a dispersion diagram virtually identical to Fig. 1 of Gary and Sanderson's local Vlasov theory.<sup>2</sup> In addition to this, ROOTS provides nonlocal solutions, which will be useful in most simulations with steep density gradients. Some details will appear in the next QPR.

We found the ROOTS results in the linear local dispersion solutions to agree with Cohen *et al.*<sup>3</sup> ROOTS predicts the linear marginal stability at  $L_n/\rho_i = 5.0$  for  $m_i/m_e = 100$ ,  $\omega_{pe}/\omega_{ce} = 1$  (where  $L_n = \frac{1}{n} \frac{dn}{dx}$ ,  $n(x)$  is the guiding center density,  $\rho_i$  is the ion gyroradius,  $\omega_{pe}$  and  $\omega_{ce}$  are the plasma and cyclotron frequencies of electrons).

Detailed dispersion diagrams for a choice of future simulation parameters will be given in the next QPR.

<sup>1</sup>M. J. Gerver, "ROOTS, A Dispersion Equation Solver", UCB/ERL Memorandum No. M77/27 (Oct. 31, 1976).

<sup>2</sup>S. P. Gary and J. J. Sanderson, "Density Gradient Drift Instabilities: Oblique Propagation at Zero Beta", *Phys. Fluids* 21, pp. 1181-1187 (July, 1978).

<sup>3</sup>B. I. Cohen, N. Maron and T. D. Rognlien, "A Local Theory of Nonlinear Ion Dynamics in a Drift-Cyclotron Mode", OA5, *Fusion Theory Conference* (1978).

## B. PLASMAS WITH FIELD REVERSAL\*

Douglas Harned

### (1) MAGNETIC RECONNECTION

The problems of magnetic reconnection have been examined to see if an analogy can be made between the bow shock and the x-points in a field-reversed mirror configuration. The situations appear to be considerably different because of the requirement for particle flow across magnetic field lines in the reconnection.<sup>1</sup> While the solar wind provides such a flow in the magnetosphere, the relatively low particle density in the regions surrounding the x-points in the field-reversed mirror suggest that reconnection will not occur at a significant rate. There is the possibility, however, that in a fusion plasma, alpha particles could provide a significant source for the reconnection process.

Additionally, some facility was developed with the particle trajectory code TIBRO-X.<sup>2</sup> It would be possible with this code to investigate single particle behavior in simple reconnection schemes by replacing the gravitational force with an electric one. New models similar to the current sheet models of Speiser<sup>3</sup> could be examined.

### (2) STABILITY OF REVERSED-FIELD CONFIGURATIONS

An investigation has been started to analyze the stability of infinite layer (infinite in  $z$ ) reversed-field configurations to modes having  $k_z = 0$ . One motivation for this study has been the recent results of simulations at Livermore<sup>4</sup> and Cornell<sup>5</sup> showing the instability of such

\*This section was in Section II: Simulation in the past QPR, but should have been in Section I: Theory.

<sup>1</sup>Vasyliunas, V. M., "Theoretical Models of Magnetic Field Line Merging, I", Rev. of Geophysics and Space Physics 13, 303-336 (1975).

<sup>2</sup>J.D. Hansen and R. S. Devoto, "TIBRO-X: A Code to Compute Trajectories of Charged Particles in Magnetic Fields", UCRL-52189 (1976).

<sup>3</sup>Speiser, T. W., "Particle Trajectories in a Model Current Sheet, Based on the Open Model of the Magnetosphere, with Applications to Auroral Particles", J. of Geophysical Research 70, 1717-1728 (1965).

<sup>4</sup>Byers, J. A., private communication (1978).

<sup>5</sup>Friedman, A., private communication (1978).

a cylinder. We are beginning by analyzing a slab of plasma containing a thin beam (the limit of an infinite radius cylinder). Hopefully this will provide insight into the stability of such configurations and may help determine whether the instabilities seen elsewhere are real or numerical in nature.

## Section II SIMULATION

### A. QUASILINEAR SIMULATION OF A MIRROR MACHINE

Dr. Y. Matsuda with Dr. H. L. Berk (LLL)

A report is in preparation titled "Quasilinear Simulation of the Drift-Cyclotron Loss Cone Instability".

### B. SELF-HEATING OF A 1d THERMAL PLASMA

A. Peiravi

This project was completed this past quarter. The results were reported at Monterey (See Section V) and an ERL Report is completed, to be mailed soon.

Dr. Hirotada Abe (Dept. of Electronics, Kyoto University) has kindly called our attention to his work<sup>1</sup> dealing with the same subject. We recommend this work to our readers.

### C. ONE DIMENSIONAL ESI CODE FOR SHEATHS

Yu-Jiuan Chen (Prof. C. K. Birdsall)

No special work to report this quarter.

### D. PARTICLE TRAJECTORIES IN A CUSP FIELD

Yu-Jiuan Chen (Prof. C. K. Birdsall)

No special work to report this quarter.

<sup>1</sup>H. Abe, J. Miyamoto and R. Itatani, "Grid Effects on the Plasma Simulation by the Finite-Sized Particle", J. Comput. Phys. 19, pp. 134-149 (Oct., 1975)

Section III  
CODE DEVELOPMENT AND MAINTENANCE

A. ESI CODE

Dr. W. M. Fawley

(1) *Adaptations of ESI to use Post-Processor "ZED"*

We have decided to adapt the much-used 1½d electrostatic code ESI to produce time history files that can be read and manipulated by the post-processor program ZED. ZED is normally used with the output of the 2½d code ZOHAR and permits the user to investigate plasma simulation time histories of quantities such as electric potential and potential particle moments through means such as Fourier analysis and cross-correlation. It is necessary to change ESI to run under the CHATR compiler. In the next QPR, we plan to give extensive details concerning these changes.

(2) A. B. Langdon has changed the loader for  $B \neq 0$ . Consult ESIREP in ESILIB.

B. EM1 CODE

Dr. W. M. Fawley

ZED will also be set up for EM1 in the near future.

C. ELECTROSTATIC 2½d CODE DEVELOPMENT (EZOHAR)

W. M. Nevins, Dr. Y. Matsuda

This work is nearly complete, as reported at Monterey (see Section V) and is being prepared for publication, with the title "A New Particle Simulation Model for a Bounded Plasma", by Nevins and Matsuda.

An initial application of the code will be given in a paper titled "Simulation of the Drift Cyclotron Instability" by Matsuda, in preparation.

D. ESI + EFL CODE

J. K. Lee (Prof. C. K. Birdsall)

A paper titled "Particle-Fluid Hybrid Codes Applied to Beam-Plasma, Ring-Plasma Instabilities" was presented at Monterey (see Section V). The abstract is as follows:

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PARTICLE-FLUID HYBRID CODES APPLIED TO BEAM-PLASMA, RING-PLASMA INSTABILITIES

J. K. Lee and C. K. Birdsall  
Electronics Research Laboratory  
University of California, Berkeley CA 94720

When a beam-plasma type instability is simulated using a particle code, the plasma part (which is usually 100 to 1000 times denser than the beam part) requires a lot of simulation particles; otherwise the noise from the plasma is high enough to obscure the instability itself. One example of this crucial effect can be observed in the simulation of the so-called velocity-space ring-plasma (flute-like) instability, which arises due to the interactions of energetic beam ions (a ring in velocity-space) with cooler Maxwellian plasma ions, carried out through a particle code by C. K. Birdsall et al.<sup>1</sup> Upon the suggestion of A. B. Langdon, we constructed a hybrid code (the idea itself is by no means new) using a particle code (ESI by A. B. Langdon) for the simulation of beam particles and a fluid equations for the representation of the plasma component. One simple example of a fluid is an Eulerian fluid, linearized (EFL). The linearization is to be monitored but generally it is justifiable since the plasma component stays linear in many beam-plasma type interactions. Another possible fluid would be a non-linear Lagrangian fluid (LAF) suggested by W. M. Nevis. These two fluid schemes will be discussed together with successful applications of a hybrid code combining ESI and EFL (two versions: electrostatic and electromagnetic) to the study of linear and nonlinear evolution of the above ring-plasma instability. The use of a hybrid for a beam-plasma type instability has merits of eliminating the plasma particles as well as the noise from them. For computing time on a CDC 7600 (LLL MFECC "A" machine) the hybrid (ESI + EFL) takes about 0.14 sec per time step ( $\approx 16$  usec per time step per particle) and this could be further improved through optimization.

I. STRUCTURE OF HYBRID CODES

The electrostatic hybrid (ESI + EFL) consists of ESI for the beam and EFL for the plasma. For EFL, the linearized two-fluid equations in finite-difference form is:

$$\frac{v_{j+\frac{1}{2}}^{n+\frac{1}{2}} - v_{j+\frac{1}{2}}^{n-\frac{1}{2}}}{\Delta t} = \frac{q}{m} \left[ E_{j+\frac{1}{2}}^n + \left( \frac{v_{j+\frac{1}{2}}^{n+\frac{1}{2}} + v_{j+\frac{1}{2}}^{n-\frac{1}{2}}}{2} \times B_0 \right) \right]$$

$$-\frac{\gamma v_t^2}{\rho_0} \left( \frac{\rho_{j+1}^n - \rho_j^n}{\Delta x} \right)$$

$$\frac{\rho_j^{n+1} - \rho_j^n}{\Delta t} = -\frac{\rho_0}{\Delta x} \left( \frac{v_{j+\frac{1}{2}}^{n+\frac{1}{2}} - v_{j-\frac{1}{2}}^{n+\frac{1}{2}}}{\Delta x} \right) .$$

The leap-frog scheme is time and space centered as in Fig. 1(a). The electromagnetic hybrid code (EMI +EFL) is constructed by combining EMI (relativistic and nonrelativistic electromagnetic particle code<sup>2</sup>) with the properly modified electromagnetic version of EFL, whose leap-frog scheme shown in Fig. 1(b) is similar to the electrostatic EFL [Fig. 1(a)] except for some additional quantities kept.

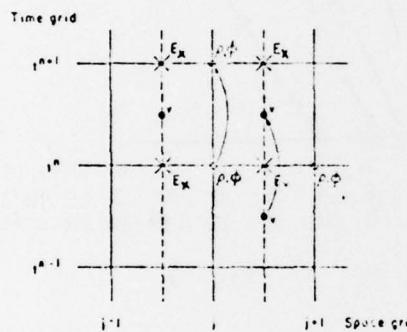


Fig. 1(a)

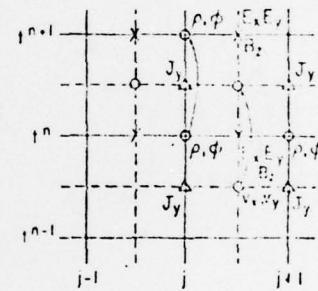


Fig. 1(b)

### III. APPLICATION OF A HYBRID CODE

The use of ESI + EFL in simulation of an unmagnetized beam-plasma instability yields results (linear and nonlinear) almost identical with a particle code. A more important application of this code is to the above ring-plasma instability. Simulations using a hybrid code (marked x in Fig. 2) provide remarkable verification of the linear Vlasov theory (continuous curves in Fig. 2) especially when compared to particle code results (Ref. 1, marked 0 in Fig. 2). This excellent agreement extends to a wide range of plasma parameters whether electrostatic or electromagnetic.

Hybrid simulations also provide extensive information about nonlinear evolution of this instability such as beam spreading, average slowing down, and saturation level, which agree nicely with some analytic explanations.

### III. LIMITS ON THE LINEARITY OF THE FLUID PLASMA

The linearity assumption is good as long as the perturbed plasma velocities ( $v_i$ ) remain small compared to the wave phase velocity ( $\omega/k$ ). Fig. 3 shows that this criterion is satisfied in many cases except for strong beam cases (e.g.,  $R = n_{beam}/n_{plasma} \approx 0.1$  to 1) near saturation times. In order to follow the nonlinearity of the fluid plasma, changing to the Lagrangian fluid (LAF) model will be discussed.

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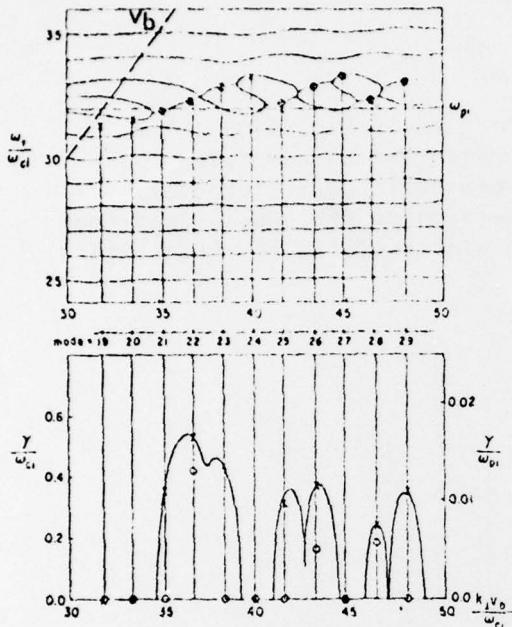


Fig. 2

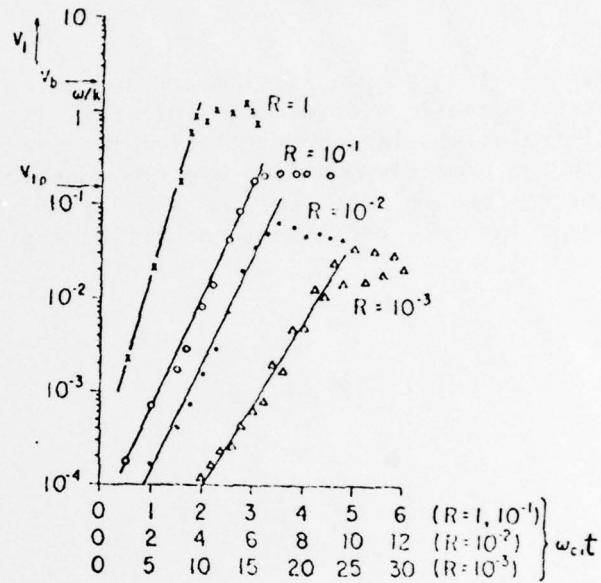


Fig. 3

<sup>1</sup>C. K. Birdsall, M. J. Gerver and N. Maron, Bull. Am. Phys. Soc. 21, p. 1148, 1976.

<sup>2</sup>A. B. Langdon, Ph.D. Thesis, Princeton University (1970); B. I. Cohen, M. A. Mostrom, D. R. Nicholson, A. N. Kaufman and C. E. Max, Phys. Fluids 18, 470, 1975.

A paper will be prepared and submitted to the Journal of Computational Physics next quarter, which will consist of the detailed code algorithm with two major applications, namely to the magnetized ring-plasma instability and to the unmagnetized beam-plasma instability [specially the off-peak saturation effects presented in the QPR II (July, 1977), pp. 5-14)].

E. 1 $\frac{1}{2}$ d PARTICLE-FLUID HYBRID MODEL FOR THE DRIFT-WAVE INSTABILITIES  
 Yu-Jiuan Chen

A simulation method is proposed for the study of the lower-hybrid-drift instability and the mirror-drift-cone instability in the sheath region. For simplicity, it is assumed that  $T_e \ll T_i$ , and the finite plasma beta effects (electromagnetic effects and  $\nabla B_o$  electron orbit modification) are negligible. Moreover, primary emphasis is placed on high-frequency perturbations characterized by

$$\omega_{ci} \ll |\omega_r + i\gamma| \approx (\omega_{ce}\omega_{ci})^{\frac{1}{2}} \equiv \omega_h \ll \omega_{ce}, \quad (1)$$

$$a_i^{-2} \ll k_{\perp}^2 \leq a_e^{-2} \quad \text{and} \quad a_e^2 \ll L^2 \quad (2)$$

where  $\omega_{cs} = |e_s|B_o/m_s c$  is the gyrofrequency,  $a_s = (2T_s/m_s \omega_{cs}^2)^{\frac{1}{2}}$  is the local Larmor radius, and  $L^{-1} = \frac{\partial n}{\partial y} \Big|_{y_o} / n$  is the density scale length. Therefore, we can employ the local approximation in the density gradient direction and treat electrons as a strongly magnetized fluid and ions as unmagnetized particles.

In general, the initial plasma configuration is illustrated in the slab geometry as shown in Fig. 1. We consider perturbations localized about  $y = y_o$ , and the local equilibrium magnetic field primarily in the  $z$ -direction with

$$\underline{B}(x) = \hat{e}_z B_o(y_o) + \hat{e}_x B_o(y_o) \frac{y - y_o}{L_s}$$

in the vicinity of  $y = y_o$ , where  $L_s^{-1} \equiv (\partial B_x / \partial y) \Big|_{y_o} / B_o(y_o)$  is the length scale characterizing the magnetic shear. The electron drift across the magnetic field  $B_o \hat{e}_z$  with the mean fluid velocity

$$v_{x_e} = v_E + v_{de}, \quad (4)$$

where  $v_E = cE_y^0 / B_o$  is the  $E \times B$  drift velocity,  $v_{de} = (T_e/m_e \omega_{ce}) \frac{\partial \ln(nT_e)}{\partial y} \Big|_{y_o}$  is the electron diamagnetic drift velocity, and  $n(y) = n_e(y) \approx n_i(y)$  is the

density. For the electron fluid drifting through a stationary ion background, the electron  $E \times B$  drift motion and the inhomogeneities in  $n$ ,  $B$ , and  $T_e$  provide the free energy to drive instabilities.

As  $L_s \rightarrow \infty$ , i.e., no magnetic shear, a 1½d electrostatic particle fluid model (ES1 + FLUID) can be used to simulate these two kinds of instabilities in  $E \times B_0$  direction, i.e.,  $x$  direction, instead of 2½d particle simulation.<sup>1</sup> A 1½d magnetized electron fluid drifts with velocity  $v_{x_e}$  through a local Maxwellian 1d ion background for the lower-hybrid-drift instability, or loss cone 1d ions for the mirror-drift-cone instability. The electron  $E \times B$  drift and the inhomogeneities are taken care through the drift velocity  $v_{x_e}$ . Since there is no boundary effect in the  $x$  direction for the slab geometry, the periodic boundary condition usually used in ES1 code is appropriate for this case (shown in Fig. 2). If the magnetic shear is considered, this model can be generalized to 2½d ( $x$ ,  $y$ ,  $v_x$ ,  $v_y$ , and  $v_z$ ).

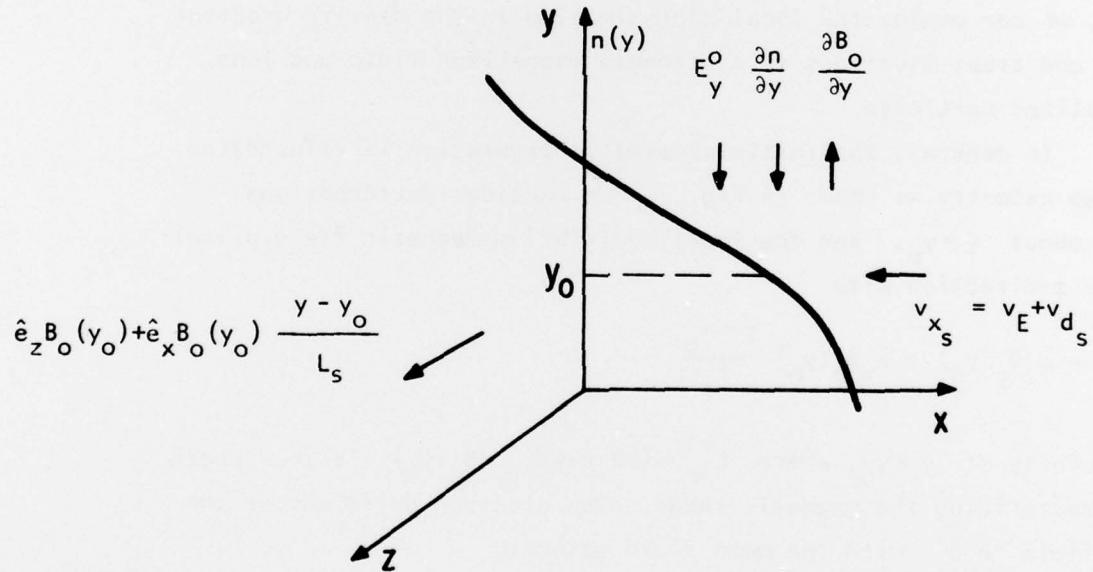


Fig. 1 Slab Geometry and Coordinate System

<sup>1</sup>D. Winske and P. C. Liwer, "Particle Simulation Studies of the Lower Hybrid Drift Instability", Phys. Fluids 21(6), pp. 1017-1025 (1978).

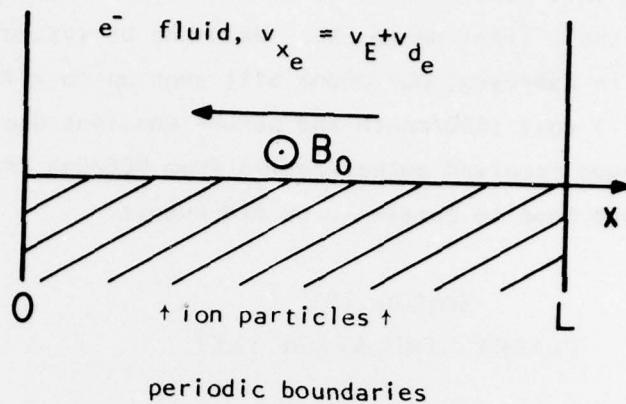


Fig. 2 1½d Particle-Fluid Hybrid Model

F. RJET, PDP 11/04

Dr. W. M. Fawley

With the exception of the Versatec controller unit described below, all necessary hardware has been installed in the UCB remote user system. The PDP 11/04 has been moved and secured into place away from the terminal rooms 119ME and 119MD where its fan noise would have interfered with mental concentration. The DZ-11A multiplexer has been installed and the 8 terminal lines run to the proper rooms.

In order to run our Versatec electrostatic printer off the PDP 11/04 directly, it was necessary to order in mid-June a PDP 11/DMA controller Model #121 from Versatec. Funds for this acquisition were requested from DOE in April and received in June 1978. An extra long 60' cable was also ordered to run from the PDP 11/04 to the Versatec unit. Delivery is expected by late August.

The software necessary to run the PDP 11/04 as a terminal concentrator still has not been delivered from Livermore. The primary difficulty appears to be the DEC's DMC11 network links not working according to specification. Consultation between LLL and DEC is in progress; until the software arrives, the UCB PDP 11/04 must sit idle.

We have initiated efforts to obtain an LBL extension phone so that we may use their tie-line to LLL. When the UC system tie-line to LLL disappeared in February, our phone bill shot up to >\$1000/month. An LBL extension will cost ≤ \$20/month and permit constant use of the LLL computer. We have received authorization from DOE/San Francisco for the extension and hope to obtain it by mid-August.

#### Section IV PLASMA SIMULATION TEXT

Rewvisions of Part I have been made, to be completed in September. Part II revisions are progressing well.

#### Section V SUMMARY OF REPORTS, TALKS AND PUBLICATIONS IN THE PAST QUARTER

Four papers were presented at the *Eighth Conference on Numerical Simulation of Plasmas* at Monterey, June 28 - 30 (the Proceedings published up to four page abstracts), as follows:

- (1) J. K. Lee and C. K. Birdsall, "Particle-Fluid Hybrid Codes Applied to Beam-Plasma, Ring-Plasma Instabilities".
- (2) A. Peiravi and C. K. Birdsall, "Self-Heating of 1d Thermal Plasmas: Comparison of Weightings; Optimal Parameter Choices".
- (3) W. M. Nevins, "Diagnostics — The Business End of a Plasma Simulation Code".
- (4) Y. Matsuda, W. M. Nevins and M. Gerver, "A New Particle Simulation Model for a Bounded Plasma".

Prof. C. K. Birdsall chaired one of the six oral sessions.

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